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CALCULATION OF LIGHTNING CHANNEL HEIGHT AND RETURN STROKE PROPAGATION SPEED FROM ELECTROMAGNETIC FIELD WAVEFORMS

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ABSTRACT

For obtaining typically observed or measured lightning electromagnetic field characteristics of the return stroke channel current different models can be used. Modified transmission line model with exponential decay with height, as an engineering model, and the functions earlier proposed by the authors for the channel-base current approximation, are used in this paper for lightning electric and magnetic field computation. The relationships between the lightning channel height, the return stroke propagation speed, the distance from the channel-base and time of the discontinuity appearance in electric and magnetic field waveforms are presented in this paper. These relationships can be used for obtaining any of these quantities of interest from other three experimentally determined or estimated. For different lightning channel heights the electric and magnetic field at ground surface points at different distances from the channel-base are presented in the paper for the chosen return stroke propagation speed.

Index Terms - Lightning, electromagnetic field, antenna, return stroke, channel-base current function

1. INTRODUCTION

Different lightning return stroke channel models are described in [1]. Modified transmission line model with exponential decay with height (MTLE) [2] is often used as an engineering model for lightning electromagnetic field (LEMF) calculations. The function CBC proposed in [3] and the function NCBC proposed in [4] for the approximation of channel-base currents, are used in this paper. Their parameters choice is analyzed in detail in [3] and [4]. The CBC function is simpler, but NCBC can better reproduce the channel-base current characteristics of the function proposed in [5] and often used by other authors. Relationships between the lightning channel height, the return stroke propagation speed, the distance from the channel-base and time of the discontinuity appearance in electric and magnetic field waveforms are presented in this paper. These relationships can be used for obtaining any of these four quantities of interest in the case of other three experimentally measured or estimated. It is also shown in this paper that these relationships can be used independently on the chosen channel-base current waveshape. For different lightning channel heights and for the chosen return stroke propagation speed the results for LEMF at ground surface points at different distances from the channel-base are presented in the paper.

2. THE RETURN STROKE SPEED

Lightning return stroke speed is one of the main parameters in lightning modeling, so as in evaluating lightning-induced effects [6]. It is known that the return stroke speed may vary along the lightning channel. Techniques for measuring return stroke speed were discussed by Idone and Orville [7]. "The optically measured return stroke speed probably represents the speed of the region of the upward-moving return stroke tip where power losses are the greatest. The peak of the power loss wave likely occurs earlier in time than the peak of the current wave" [8]. It was concluded in [8] that the often assumed relationship between the return stroke speed and the peak current is generally not supported by experimental data. On the basis of measurements for both natural and rocket-triggered lightning the propagation speed of a negative return stroke (both first and subsequent) is averaged over the channel below the lower cloud boundary and estimated to be from one-third to one-half of the speed of light. The negative return stroke speed within the bottom 100m or so is estimated to be from one-third to two-thirds of the speed of light. For a positive return stroke this speed is also of the order of 10^8 m/s.

In most of the return stroke models and LEMF calculations the value of the return stroke speed is assumed to be constant over the channel. For the negative return stroke the speed may vary non-monotonically along the channel, initially increasing and then decreasing with height, and for the positive return stroke there are contradicting data regarding its variation along the channel [8]. There are also discussions in [1] and [9] about the attempts of return stroke speed estimation by different authors.

In this paper one new and different approach is presented, trying to make use of electric and magnetic field waveforms at surface points at different distances from the lightning channel-base and the obtained relationships. If the return stroke speed is estimated in another way, then the use of them can be made for estimating lightning channel height.

3. THE DERIVED RELATIONSHIPS

In the case of a thin straight vertical antenna modeling of the lightning channel it is necessary to choose a certain height of that antenna [10]. In natural cases there is a height at which the discharge stops for a while, even if it would be continued later and then stopped at some different height. Can this be noticeable in experimentally measured lightning electric and magnetic field waveforms? This paper presents results showing how this might be used for determining the lightning channel height or the return stroke speed.

On the basis of the governing relation of transmission line models, it can be noticed [11] that the interrupt of the lightning channel at a certain height from the ground results in the discontinuity appearance in time moment t_d after the time of LEMF appearance at that point, $t_0 = r/\mathrm{c}$, in both electric (Fig.1) and magnetic field (Fig.2) in a similar way at the distances of kilometers from the lightning channel-base.

For a chosen lightning channel height *H* and a return stroke propagation speed *v*, at a distance *r* from the channel-base, the time of the discontinuity appearance can be calculated from the following expression

$$t_d = H\,v^{-1} + \left(\sqrt{H^2 + r^2} - r\right)\mathrm{c}^{-1}, \tag{1}$$

for c the speed of light. The results are presented in the following table for $v = 1.3\cdot 10^8$ m/s which is usually used in calculations as the average return stroke speed. If t_d is determined from the measured LEMF waveforms, and the return stroke propagation speed is assumed as $v = 1.3\cdot 10^8$ m/s, then the lightning channel height can be determined from the expression

$$H = \left(\mathrm{c}\,t_d + r - \sqrt{r^2 + v^2 t_d^{\,2} + 2v^2 r t_d\,\mathrm{c}^{-1}}\right)\left(\mathrm{c}\,v^{-1} - v\,\mathrm{c}^{-1}\right)^{-1}. \tag{2}$$

At the basis of experimentally determined lightning channel height *H* and for the time of the discontinuity appearance t_d in electric and magnetic field waveforms, the return stroke propagation speed along the channel could be determined from the expression

$$v = H\left(t_d + r\,\mathrm{c}^{-1} - \left(\sqrt{H^2 + r^2}\right)\mathrm{c}^{-1}\right)^{-1}. \tag{3}$$

The NCBC channel-base current function is

$$i(t) = \begin{cases} I_m\left[\tau\,\mathrm{e}^{\,(1-\tau)}\right]^{a}, & 0 \le \tau \le 1 \\ I_m \sum\limits_{i=1}^{n} c_i\left[\tau\,\mathrm{e}^{\,(1-\tau)}\right]^{b_i}, & 1 \le \tau < \infty \end{cases} \tag{4}$$

for $\tau = t/t_m$, I_m the maximum current at t_m, and the parameters a, b_i and c_i determining the current waveshape. For *i*=1 it becomes the simpler CBC function.

Table 1 - Time t_d in μs of the discontinuity appearance (counted from t_0 of LEMP appearance at a distance *r* in km) for different channel heights *H* in m

Time t_d (μs)				
The distance *r* (km)	Channel height *H* (m)			
	2600	4500	7000	12000
0.5	27.16	48.04	75.57	130.68
1	25.95	46.65	74.08	129.11
5	22.12	40.37	65.85	118.97
200	20.06	34.78	54.25	93.51

4. LEMF RESULTS

For the distance of 5km from the channel-base the results for vertical electric field for three different channel heights and for the channel-base current function CBC [3] with parameters *a*=1.5, *b*=0.02, $t_m = 0.5826$μs and $I_m = 11$kA, (approximately as the function in [5]), are presented in Fig.1, and for azimuthal magnetic field in Fig.2. Modified transmission line model (MTLE) with the channel current exponential decay with height *z'* is used, so $i(z',t) = i(0,t)\exp(-z'/\lambda)$, for $\lambda = 4500$ m. The corresponding time intervals t_d of the discontinuity appearance in these waveforms can be noticed in Figs.1-9 for the chosen channel heights and the return stroke speed $v = 1.3\cdot 10^8$ m/s, also as in Table 1.

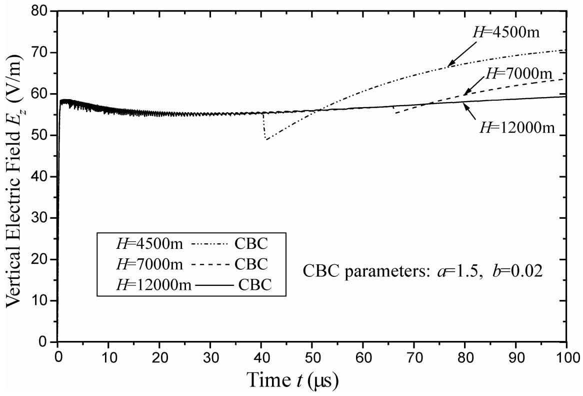

Figure 1 Vertical electric field at 5km for three different channel heights and for the CBC function

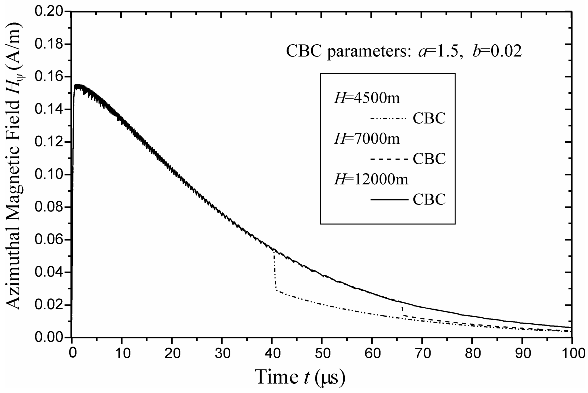

Figure 2 Azimuthal magnetic field at 5km for three different channel heights and for the CBC function

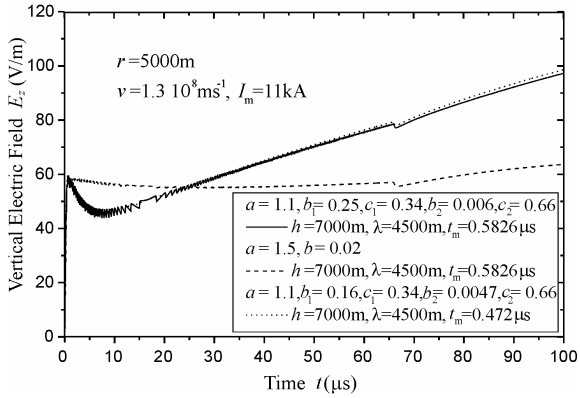

Figure 3 Vertical electric field at 5km for three different CBC&NCBC channel-base current functions

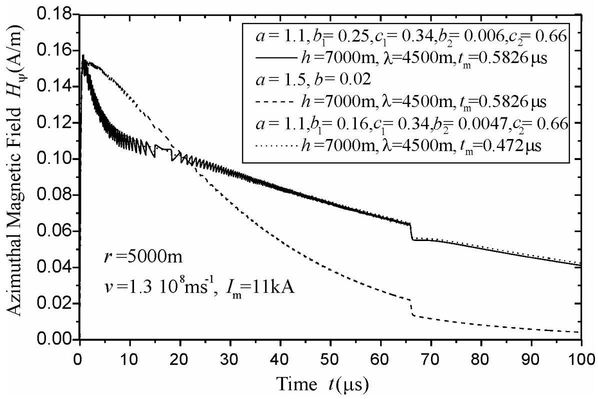

Figure 4 Azimuthal magnetic field at 5km for three different CBC&NCBC channel-base current functions

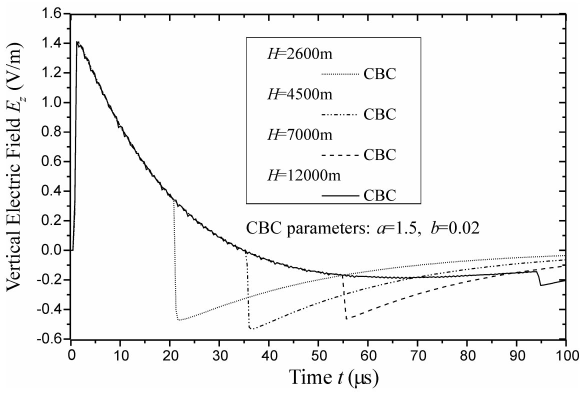

Figure 5 Vertical electric field at 200km for four different channel heights and for the CBC function

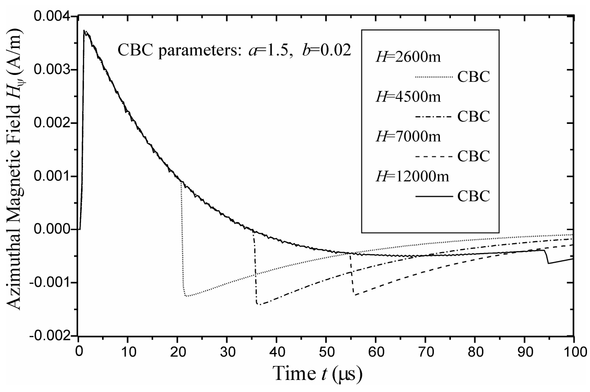

Figure 6 Azimuthal magnetic field at 200km for four different channel heights and for the CBC function

For determining the electric and magnetic field above perfectly conducting ground from a straight vertical finite height antenna with a simple triangular current pulse in the channel-base the results are presented in [10]. At three different distances, for the speed $v = 1.3\cdot 10^8$ m/s and the height *H*=4km as in [10], the time of the discontinuity appearance t_d can be calculated from (1), and for the distance *r*=1km the value $t_d = 60.41\,\mu\text{s}$ is obtained, for *r*=10km the value $t_d = 52.57\,\mu\text{s}$, for *r*=100km $t_d = 50.27\,\mu\text{s}$. The same time moments can be noticed in both electric and magnetic field waveforms for the three distances in the Fig.3 of paper [10]. It is interesting that the current derivative is constant in the rising part (equal to $10\,\text{kA}/1.2\,\mu\text{s}$), different from the current derivative of [5], that the channel-base current is of a finite time duration (chosen to be $25\,\mu\text{s}$) and different shape than usually used for such calculations, but the results from [10] prove the derived expressions (1)-(3).

This can be noticed also for the model proposed in [12], for *H*=9km, *r*=100km and $v = 1.3\cdot 10^8$ m/s, for which the value of $t_d = 70.58\,\mu\text{s}$ is obtained from (1).

The three different channel-base current waveshapes are chosen to show that these relationships are not influenced by the channel-base current function shape and its first derivative and that t_d is the same in these cases (Figs.3 and 4). For the first chosen channel-base current the NCBC function parameters are $I_m = 11\,\text{kA}$, $t_m = 0.5826\,\mu\text{s}$ and $a = 1.1$, $b_1 = 0.25$, $c_1 = 0.34$, $b_2 = 0.006$, and $c_2 = 0.66$. For the second channel-base current the CBC parameters are chosen as $I_m = 11\,\text{kA}$, $t_m = 0.5826\,\mu\text{s}$, $a = 1.5$, $b = 0.02$, and for the third channel-base current the NCBC parameters are $I_m = 11\,\text{kA}$, $t_m = 0.472\,\mu\text{s}$, $a = 1.1$, $b_1 = 0.16$, $c_1 = 0.34$, $b_2 = 0.0047$, and $c_2 = 0.66$ (the most adequate to the function in [5], with the same I_m and t_m).

The results for four different channel heights and for the channel-base current function with parameters $I_m = 11\,\text{kA}$, $t_m = 0.5826\,\mu\text{s}$, *a*=1.5 and *b*=0.02, for vertical electric field are presented in Fig.5, and for azimuthal magnetic field in Fig.6, for *r*=200km.

The effect of lightning channel height at the distance of hundreds of meters is different. For example at *r*=500m (Fig.7) and *r*=1km (Fig.8) from the channel-base the increase of the vertical electric field appears after time t_d from t_0.

The discontinuity is noticeable also in magnetic field waveforms at hundreds of meters from the channel-base, but as a decreasing step (Fig.9).

In experimentally obtained results for electric and magnetic field waveforms these discontinuities can be noticed and the unknown values can be estimated from relationships (1)-(3) if other quantities assumed.

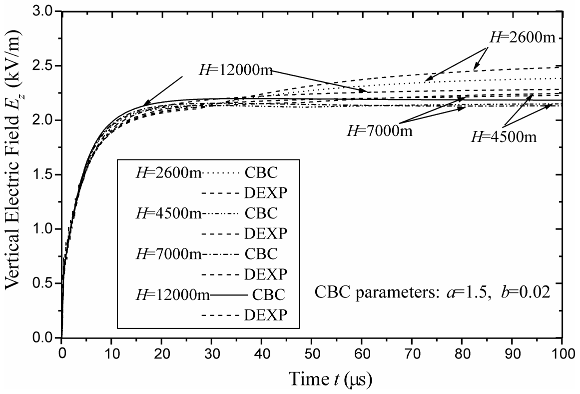

Figure 7 Vertical electric field at 500m for four different channel-base current functions

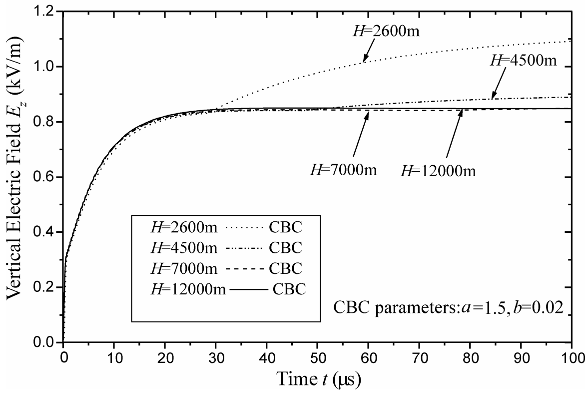

Figure 8 Vertical electric field at 1km for four different channel heights and for the CBC function

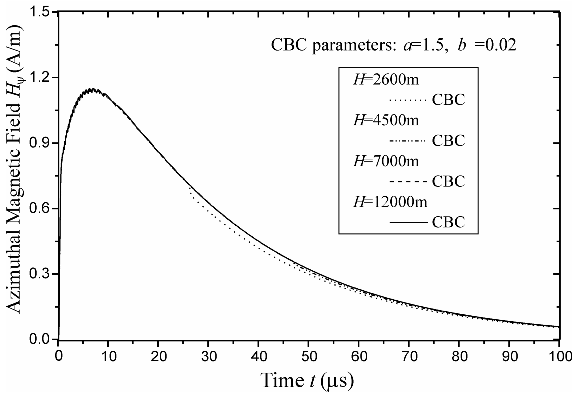

Figure 9 Azimuthal magnetic field at1km for four different channel heights and for the CBC function

5. CONCLUSION

From experimentally measured lightning electric and magnetic field waveforms, on the basis of time of discontinuity appearance at different distances from the channel-base, the return stroke speed can be estimated if the lightning channel height is assumed or known (e.g. in rocket-triggered lightning experiments). The derived relationships can be used also for estimating the lightning channel height if the return stroke speed is assumed. The distance from the lightning channel-base can also be estimated using measured electric and magnetic field waveforms and chosen return stroke speed and the channel height.

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